Indian Journal of Engineering & Materials Sciences
Vol. 27, April 2020, pp. 410-417

Characteristic investigation of cutting-force measuring dynamometers

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Received: 08 August 2019 ; Accepted: 12 December 2019

Despite having significant role to measure the forces in tillage, medical and various diagnostic studies, force dynamometers are extensively employed in cutting-force monitoring and measurement. In this paper, an investigation of various cutting-force measuring dynamometers based on characteristics and design has been carried out. Characteristic based investigation helps in deciding about various important parameters in the development of cutting-force measuring dynamometers. Literature available has been studied to cleanly select the characteristic of dynamometer that govern their fundamental design. Various characteristics of dynamometer materials have been discussed. Shape of deforming elements used by researchers in the development of dynamometer has been discussed. Sensing elements that are often used in the development of cutting force measuring dynamometers have been studied with relative merits. Process of calibration for dynamometer with its importance has also been considered. Various metrological features obtained by researchers have been discussed and conformity of calibration procedure to standards like ISO 376 along with IS: 4169-1988 have been considered. The present work will give a newer insight to the researchers in the field benefitting them to understand the characteristic parameters, to make decision in their selection correctly and to have the knowledge of procedural design for the same.

Keywords: Cutting force dynamometer, Ring theory, Calibration

1 Introduction

Measurement of cutting-forces is always an area of interest for the researchers working in the field of manufacturing and metal-cutting as the cutting-force is an indicative of the fulfilment of machining task. Cutting-force determination is important in the sense that it gives clear idea of chip-formation and condition of the cutting-tool with chatter vibrations[1,2]. It also helps in characterization of work material and optimization of tool-geometry[3]. Manufacturing and cutting-processes can be effectively monitored and optimised by measuring the cutting-forces in all the directions. It has been observed that the forces during the cutting-processes are the measure of heat generated at tool-work interface and therefore have control over tool-wear[4], accuracy and quality of machined surface[5-7] so produced.

It should also be noted that the cutting-force generated during metal cutting-processes can not be measured directly instead its effect can be sensed with the help of force measuring dynamometer comprising force-sensors. The effects of the cutting-force are called signals representing deformation, elastic deflection, strain, *etc*. and may require conditioning for accurate and reliable measurement of the cutting-forces[8,9].

Dynamometers are devices extensively employed to measure the forces over the years. Though these devices are used extensively to measure the cutting forces in machining processes, they have their application to measure the forces on Plough Bodies in Tillage Studies also[10-13] where the dynamometers are primarily developed to monitor the forces and the moments experienced due to soil reaction in different planes[14,15]. Another application of dynamometers is to measure the forces for tool wear monitoring and process control[16]. Force-signals developed during machining are considered as the carriers of information relating to machining processes and are therefore employed to devise a dynamometer for diagnostic techniques[17-19] and tool-wear monitoring[20-22]. Dynamometers also have their applications in the study of optimised process-parameters and machining process monitoring since it has also been observed that the cutting forces are mainly affected by process parameters[8,9].

Literature is available for the design, development and testing of dynamometers for the measurement of

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cutting forces in various machining process like turning[23-26], drilling, milling, boring and similar processes. Different approaches are considered in designing dynamometers for turning[27-30] and drilling and allied processes[31] with the condition as to where dynamometer is to be mounted; at tool or under work-table. Generally the dynamometer design becomes simpler if it is to be attached with the one which remains stationary during cutting processes. Turning dynamometers are different in terms of design than drilling, milling and boring dynamometers with the reason that dynamometers are placed with the tool which remains stationary during machining in turning. Contrary to this, dynamometer are usually attached with the work in cutting-processes like drilling, milling, boring, *etc.* which remains stationary during cutting-processes. Rotating face-milling dynamometer has been developed that can be mounted to hold the rotating-tool[32]. The placement of transducer-elements is therefore easier in the dynamometers attached with the either stationary work or stationary tool during cutting- processes[33,34]. Usually a similar design is adopted for development of milling[29,35], drilling[36,37] and boring dynamometers. In some cases, drilling dynamometers developed can also be used to monitor and measure the cutting forces during boring[31] and allied processes. A study for measurement of the cutting forces in oblique machining has also been conducted with dynamometers developed for shaper machine[38].

2 Design Parameters

To work on design, analysis and to conduct testing researcher may develop cutting force measuring dynamometers considering the characteristic parameters like material, deforming and the transducing element to employ, outcomes of simple ring theory, the components of measurement, calibration and metrological characterization. Selection of suitable data acquisition method can also be considered for dynamic test observations.

2.1 Dynamometer Material

Dynamometer material refers to the material to which the deforming element is made up of. In most cases deforming element has the form of a ring and therefore called as ring element. Being an essential part of any dynamometer, the ring materials should be selected considering the factors like rigidity, corrosion resistance, natural frequency, heat conductivity, linearity, frequency-response, deformation under the load and cross sensitivity[23,29].

The common materials used for deforming element are tool steel, stainless steel, aluminium and beryllium copper, the purpose is to have a material which exhibits linear variation between force exerted (within working range) and the resulting strain with negligible hysteresis and creep.

2.2 Shape of Deforming Element

In strain-gauge based dynamometers developed for multi-load component measurement a variety of elastic element shapes has been used. The element considered is usually designed on the basis of design of circular strain ring[44 - 46]. It is important to notice that for most of the applications octagonal rings are used rather than circular rings[29,30]. Octagonal rings are preferred because when compared with circular rings they require less deflection for an equivalent measured strain[47]. High stiffness is advantageous for maximum frequency response. An additional advantage of octagonal rings is that they are easier to manufacture in monolithic dynamometers[25]. For the same minimum section, the octagonal ring is stiffer than circular ones, with the stiffness being about 250 % more than stiffness of the circular ones[37]. Multi-component force dynamometers are also simple to construct with octagonal rings[33,34].

Apart from using deforming element as octagonal ring with its advantage of high stiffness, ease of machining and mounting strain gauges, researches also have developed successfully working dynamometers with deforming elements like cranked beam[39], tool post type[48], parallel beam type[24], tool-shank[26], bending beam type[28] and more. Researchers prefer octagonal rings over circular rings, contrary to this, Kumar *et al.*[43] in 2013 successfully developed a cutting-force measuring transducer with square ring-shaped deforming element and presented his work with metrological characterization for the same. He further extended his work of force measurement on modified ring-shaped transducers and developed a hexagonal-shaped deforming element and carried metrological investigation[49].

To measure the plough forces in tillage studies extended octagonal ring[10-12] and double extended octagonal rings[13,15] in various combination to have high sensitivity and low cross-sensitivity are extensively employed in the develop of force dynamometers.

2.3 Ring Theory

In designing ring based strain elements researchers consider ring theory in finding the radius and thickness of the ring element. Though the analysis of bending of a thin ring in the plane of bending was solved over a century ago[50,51], it still has its importance in practical applications of structural analysis. Fundamental equations in the analysis of bending of circular rings are obtained from equations for bending of circular cylindrical shells. In classical ring theory center-line of the circular ring is considered inextensible[52].

A loaded ring can be analysed in order to determine linear elastic mechanical behaviour by assuming it vertically and horizontally symmetrical[53]. Considering a portion of the ring as illustrated in the Fig. 1.

At a section located at angle θ from horizontal axis bending moment M_θ due to radial force F_r [14,45] can be expressed as:

$$M_\theta = M_A - \frac{F_r.r}{2}(1-\cos(\theta)) \quad \dots (1)$$

M_A can be obtained by considering strain energy *U* stored and making use of Castigliano's theorem for vertical deflection *δ* in the ring section considered.

$$U = \int_0^{\pi/2} \frac{M_\theta^2.r}{2EI}.d\theta \quad \dots (2)$$

$$\delta = \frac{\partial U}{\partial F_r} = \int_0^{\pi/2} \frac{M_\theta.r}{EI}.\frac{\partial M_\theta}{\partial F_r}\, d\theta \quad \dots (3)$$

where, using Eq. (1)

$$\frac{\partial M_\theta}{\partial F_r} = \frac{\partial}{\partial F_r}\left(M_A - \frac{F_r.r}{2}(1-\cos(\theta))\right) = \frac{\partial M_A}{\partial F_r} - \frac{r}{2}.(1-\cos(\theta)) \quad \dots (4)$$

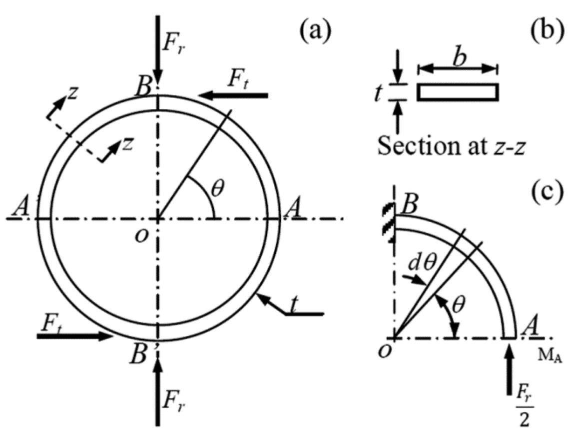

Fig. 1 — (a) A loaded circular ring (b) A portion of the ring under analysis and (c) Ring section.

by considering that point A is not rotating under the forces, M_A can be obtained as:

$$M_A = \frac{F_r.r}{2}.\left(1-\frac{2}{\pi}\right) \quad \dots (5)$$

therefore, we get bending moment at the ring surface at an angle θ under the radial force F_r

$$M_\theta = \frac{F_r.r}{2}.\left(\cos(\theta)-\frac{2}{\pi}\right) \quad \dots (6)$$

whereas the bending moment under the tangential force F_t is:

$$M_\theta = \frac{F_t..r}{2}.\sin(\theta) \quad \dots (7)$$

From Eqs (6) and (7) it is observed that the points of zero stress and strain (nodal points) at the ring surface for the forces F and P are at the angles of 39.5° and 90°. Strain gauges are mounted on these locations to read one force independent of the other. These findings are good for thin rings where $r/t \geq 5$ but for thick rings i.e. for $r/t < 3$, these results at the section considered start to depart significantly. Researchers even suggest to keep thickness larger with smaller mean radius in order to obtain maximum strain for unit deflection[14].

The strains produced on ring surfaces at nodal points (ϵ_θ) are expressed as:

$$\epsilon_\theta = \frac{M_\theta}{EI} \quad \dots (8)$$

$$\epsilon_{\theta=90^o} = 0.182\frac{F_r.r.y}{EI} \quad \dots (9)$$

$$\epsilon_{\theta=39.5^o} = 0.385\frac{F_t.r.y}{EI} \quad \dots (10)$$

where,

$$y = \frac{t}{2}, \quad I = \frac{bt^3}{12} \quad \dots (11)$$

Deflections (δ_F) under the forces F_r and F_t acting on the ring can be expressed using Castigliano's theorem[53] as:

$$\delta_{F_r} = 1.79\frac{F_r.r^3}{Ebt^3} \quad \dots (12)$$

$$\delta_{F_t} = 9.42 \frac{F_t . r^3}{Ebt^3} \qquad \ldots (13)$$

It has been found that the strain nodes considering the ring to be a circular ring at the sections where $\theta = 39.5^o$ and 90^o theoretically. Octagonal rings, frequently employed by many researchers in the development of cutting force measuring dynamometers, the strain nodes appear at different orientations. Using photoelastic technique of stress measurement, it has been estimated that the orientation of sections of strain nodes for octagonal rings are at $\theta = 50^o$ and 90^o [54].

For the design of extended octagonal rings M. J. O'Dogherty has suggested a procedure based on geometrical parameters and presented design curves for determining ring radius (*r*) and so as to obtain an appropriate ring thickness (*t*) [14].

2.4 Components of Measurement

One-component to multi-component dynamometers have their wide applications in measurement of forces. The decision on number of components is made on the number of mutually perpendicular forces to be measured by the device and the target machining process. Two or three component measuring dynamometers have their existence in cutting-force measurement for tool-condition and process-monitoring[8,9]. Three-component dynamometers are extensively employed for cutting-force measurement[23-26]. Forces during cutting in various machining processes can be measured and monitored and cutting-force measuring dynamometers have been developed for the same[55,56]. In machining-processes dynamometers developed are generally used to accurately measure the components of the cutting forces; axial, radial and tangential forces[57-59]. Three-component dynamometers are developed to monitor components of force and moments in machining[27,30] and tillage applications for process-[17,19-20] and tool-monitoring[1,2]. In order to have a control over various factors significant to the cutting-process in improving overall process performance, cutting-process monitoring is often done using multi-component dynamometers[8,9]. Researchers through their work have been found that there exists a direct strong dependency between tool-work vibrations, cutting-force and acoustic emission during cutting-processes with the condition of the tool. With this reason tool-condition can be effectively monitored by setting-up a correlation between tool-wear and the measured cutting-forces during the cutting-processes with multi-component dynamometers[4,18].

Topolnicki *et al*.[42] in 2011 developed a one-component, low-cost, high sensitivity dynamometer by making use of magnetoelectric actuator that can measure slow to fast changing forces in the range upto 5 N. A two-dimensional dynamometer was constructed successfully by Karabay in 2007 for drill-torque and thrust-force measurement[37]. There are a number of occasions where researchers have developed and tested three-component dynamometer to measure the forces during metal-cutting[23-25].

Literatures are available on tillage studies where three-component dynamometers were developed by the researchers to measure plough-forces along two orthogonal-axes and a moment in plane of orthogonal-forces[10,14].

2.5 Transducing Element

The transducing- (or sensing-) element employed commonly in the dynamometers for the measurement of cutting forces are basically of strain-gauge or piezo-electric type. In most of work conducted by the researcher, foil type electric-resistance strain-gauges are employed and if correctly affixed and calibrated, their output is expected to beer good linearity, good stability with negligible hysteresis[39]. Silicon strain-gauges are found small in sizes, lower in cost and are high in sensitivity to strain. But affixing the strain-gauges accurately demands special care. Their installation also require the use of amplifier and proper cabling. Strain-gauges are found sensitive to the changes in ambient and process temperature. But the sensitivity to temperature is not a serious concern under experimentation of short duration. It has also been found by the researcher that cutting-force measuring dynamometers with strain-gauge as the sensing element have better functional capacity[44]. The strain-gauges may have gauge-factor as high as 50 times or more and sensitivity 100 times or more[60,61].

A piezo-electric type sensing element has more rigidity. Its rigidity is considered to be nearly equal to that of the piece of steel with the same size. Though, employing the piezo-electric crystal type sensors is a relatively costly affair; approximately 20:1. It is observed that the output, i.e., electrical signal from piezo-electric crystal decays fast. But, for better rigidity during measurement and monitoring of cutting forces in cutting processes, piezo-electric type sensing elements are being preferred over strain-gauges[44].

2.6 Dynamometer Calibration

On successful completion of design and fabrication, static and dynamic calibration of the dynamometer so constructed is carried out. The process of static-calibration helps the developer to define a relation between elastic deflection of deforming element with the output voltage under loading conditions[26,30]. The static-calibration is important for the dynamometers built with strain gauge bridges where developer places the deforming elements in dynamometer in a way to have highest output voltage from strain gauge bridging. Loads are then applied on the strain-gauge based multi-axes dynamometer and incremented in steps. Atleast three tests should be conducted for each load and the readings of load and corresponding strain (output voltage) in each direction should be recorded and averaged. A calibration curve should then be prepared to read the required cutting-forces and moments on knowing the output strains[30]. Cross-sensitivity can be checked and if found small its effect can be ignored[29]. For an unavoidable cross-sensitivity, their influence should be considered in order to avoid error in the output strain readings[48]. On performing static-calibration tests one can also find coefficients of calibration for dynamometer linearity with sensitivity and repeatability[13].

The dynamic-calibration is performed to find the working frequency-range for the dynamometer on knowing its fundamental natural frequencies with dynamic characteristics. The natural frequency is considered to be the measure of dynamic stiffness of the constructed dynamometer[30]. The constructed dynamometer should have high natural frequency relative to the frequency of exciting vibration to keep the measured force unaffected by the dynamic response of the dynamometer [26].

2.7 Metrological Characterization

Metrological features related to cutting-force measuring dynamometers include repeatability, reproducibility and reversibility or hysteresis in the measurement. Resolution of dynamometer; the smallest measurable dial-reading, also serves as the good indicator of fine measurement obtained. Conformity and linearity are also expressed as metrological characteristics indicating the variation of load-readings with the average value from a polynomial fit. Another feature, the load-creep, become important for the long duration of measurement tests, affecting the quality of measurement made. All the metrological characteristics should conform to the standard released by the International Organization for Standardization (ISO). ISO 376 has been prepared for mechanical testing of metals and is used as the standard for the calibration of force-proving instruments. The mechanical testing and calibration standard of third edition ISO 376:2004 is now completely replaced by the fourth edition ISO 376:2011[62].

Work has also been done on metrological characterization of constructed force transducer by Harish *et al.*[46] following the calibration procedure based on standards like ISO 376:2004 with ±0.003 % uncertainty in the measurement. He further developed a force transducer with square-ring shaped deforming-element, metrological characterized and calibrated with conforming standard ISO 376:2004 and IS: 4169-1988[43]. In another work of metrological investigation of a force transducer with straining element of hexagonal shape, good characteristics were obtained when characterized and calibrated according to the procedure conform to the standard ISO 376:2011 with ±0.10 % uncertainty in the measurement [49]. While ring theory or the photoelastic technique can be made basis for designing mechanical transducers aiming to accurately interpret the measured cutting-forces [63].

3 Recent Development in Cutting-Force Dynamometers

Development on cutting-force measuring dynamometers are still being an area of research for many to monitor and control the process of machining as the present need of industry. In a work worth-noting researchers designed and developed an octagonal ring based cutting-force measuring device with the deforming rings having elliptic holes instead of circular ones with the aim to have an increase in the strain per unit displacement for the same given load to achieve higher sensitivity[56]. Another noticeable work has been carried out in the development of an approach to measure accurately the micro-forces during cutting by employing dynamic compensation of multi-axis force dynamometer[57,64]. Researchers has developed an innovative capacitive sensor based tool holding table-dynamometer having beam-shaped deforming elements to measure the four-component cutting-forces with high precision. This table-dynamometer can easily be used for drilling and allied processes under a rotating tool-spindle [65]. In another attempt to notice an optoelectronic based cutting-force measuring dynamometer has been developed and calibrated that work on photo-interrupters using

Table 1 — Characteristics of a dynamometer material.

Material property	Strength	High	Dynamometer assembly can sustain the external load resulting strain below the elastic limit[12].
	Rigidity	adequate	Cutting forces does not result into deflection of the dynamometer element beyond permissible limit[39].
	Corrosion resistance	high	Material does not lose its strength on having resistance against atmospheric moisture.
	Heat conductivity	High	Protection against failure by thermal softening[16].
	Deformation under the load	measurable	Predictable deformation results in accurate measurement.
Working and dynamic parameters	Natural frequency	high	Compared to the frequency of the exciting vibration, large natural frequency of dynamometer ensures recorded force unaffected by the dynamic response of the dynamometer. It usually determines dynamic stiffness of dynamometer[26].
	Sensitivity	good	Accuracy of cutting-force measurement is very closely dependent on the sensitivity of the device used[40].
	Accuracy	High	Good repeatability is the key to good accuracy[40,41].
	Linearity	good	It should conform to the deformation of strain gauges[29].
	Repeatability	High	High repeatability between force cycles ensures reliability of the measuring device.
	hysteresis	negligible	No-hysteresis prevent phase shift in readings during uneven cuts[39].
	Frequency response	wide	It characterizes dynamics of the measuring device.
	Cross sensitivity	negligible	Ring elements are usually machined identical and symmetrical to prevent cross-sensitivity[33].

Table 2 — Materials used for deforming elements.

Materials of deforming element	Design Load/Moment to measure	Reference(s)
Aluminium alloy	Upto 5N	42
EN24 alloy steel	Max. Moment = 1260 Nm Load factor = 3	10
	1 kN Axial Force	43
Steel	Max. Force= 300 lbf	39
Mild steel	Thrust: 20 lbf - 1500 lbf Torque: 15 lbf. in - 2000 lbf. in	31
Alloy steel	Max. Force of 100 kN Max. Moment of 100 kNm	11
AISI 1040 steel	Max. force of 4500N	29
AISI 4140 steel	Maximum force of 3500N in each direction	30,33
	Maximum force of 5000 N	43
ANSI 4130 steel	Draft capacity of 180 kN	15
SAE 1040 steel	Max. thrust 3500 N Max. torque 65 Nm	36,37

optical sensors with high reliability and accuracy [66]. Attempt has also been made on assessment and investigation of force measuring devices based on metrological aspects [67,68]. A comparative analysis of force measuring device has been conducted with deformation based parameters through computational and experimental methods to explore associated design related matters [69]. A diaphragm-based force measuring device has developed in which locations for sensing elements was found with the help of finite element analysis based design for industrial applications [70].

4 Conclusions

(i) Investigation has been made considering various important characteristics governing the performance of cutting-force measuring dynamometers. Dynamometer material, shape of deforming-element, ring-radius to ring-thickness ratio, components of measurement, transducing element employed, dynamometer calibration and the metrological characteristics that need to be achieved in the developed dynamometer are important to consider in the development of cutting-force measuring dynamometers. Steel as a dynamometer material has been extensively used to impart high strength, adequate rigidity and significant deformation during the load applications (refer Table 1 and Table 2) in the dynamometer assembly. Steel are easily available and have been used in wide variety as a material for deforming element from mild steel[31], plain steel[39] to alloy steel like EN24 [10,11], AISI1040/SAE1040 [29,36-37], ANSI4130 [15], AISI4140[30,33], *etc.*

(ii) Work has been carried out on testing the performance of the dynamometers developed with varying shapes of deforming elements producing measurable deformation or deflection under the load. Available literature has witnessed that circular-ring shaped deforming-element is not preferred due to difficulty in affixing strain-gauges over it. Cutting-force measuring dynamometers with octagonal, hexagonal and square-ring shaped deforming elements have been successfully developed and tested by the researchers and are preferred over circular-ring shaped deforming element due to better stiffness resulting in good frequency response. Other shapes which the deforming element can have are cranked-beam, tool-shank and bending beam, *etc.* In order to analyse the rings to determine mechanical behaviour, researcher often assume the deforming-ring to be a circular ring to make a comparative study. Photoelastic techniques or finite element analysis must be employed to determine the strain nodes when deforming ring is not circular. It has been noticed that the measured parameters are usually in good agreement with the outcomes of ring-theory for the dynamometers with thin rings. For thick rings, the measured values start deviating from the results of ring-theory. Approximate expressions based on photoelastic studies developed by Loewen and Cook can instead be used in such cases [63]. Design curves developed by O'Dogherty may also be employed in selecting an appropriate ring-radius and ring-thickness[14].

(iii) Selection of transducing element has to be made based on the simplicity and economy in design, sensitivity to temperature changes and the rigidity. Stability and linearity in measurement are also the factors to consider in selecting appropriate transducing element[44]. Prior to the practical application, constructed cutting-force measuring dynamometer must first be calibrated and metrological characterized. Calibration procedure followed and metrological features obtained have to be conform to the ISO 376:2011 [62]. Static as well as dynamic calibrations need to be given appropriate importance as the developed dynamometer has to be employed for dynamic force measurement.

(iv) It has been observed that the cutting-force measuring dynamometers have their unique role in the process and tool-condition monitoring in the modern manufacturing industry. New materials that are lighter but high in strength should also be considered in the development of deforming elements in the future. High strength aluminium alloys may be considered appropriate as the material for deforming elements. Authors felt that there are scope for the optical sensors to be incorporated in designing cutting-force measuring dynamometers for better rigidity and ease of measurement.

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